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June 3, 2004

Status of Cold Dark Matter Searches

Dan Bauer, Fermilab

Introduction

- Scientific case compelling for cold dark matter; WIMPs are a likely candidate
- Take the experimental approach; let's see what's out there…

Direct Detection of WIMPS

- How does one go about this?

A 'typical' experiment - Cryogenic Dark Matter Search (CDMS)

- First results from CDMS at Soudan

The future of direct detection

- Sensitivity of CDMS at Soudan
- The competition

Summary

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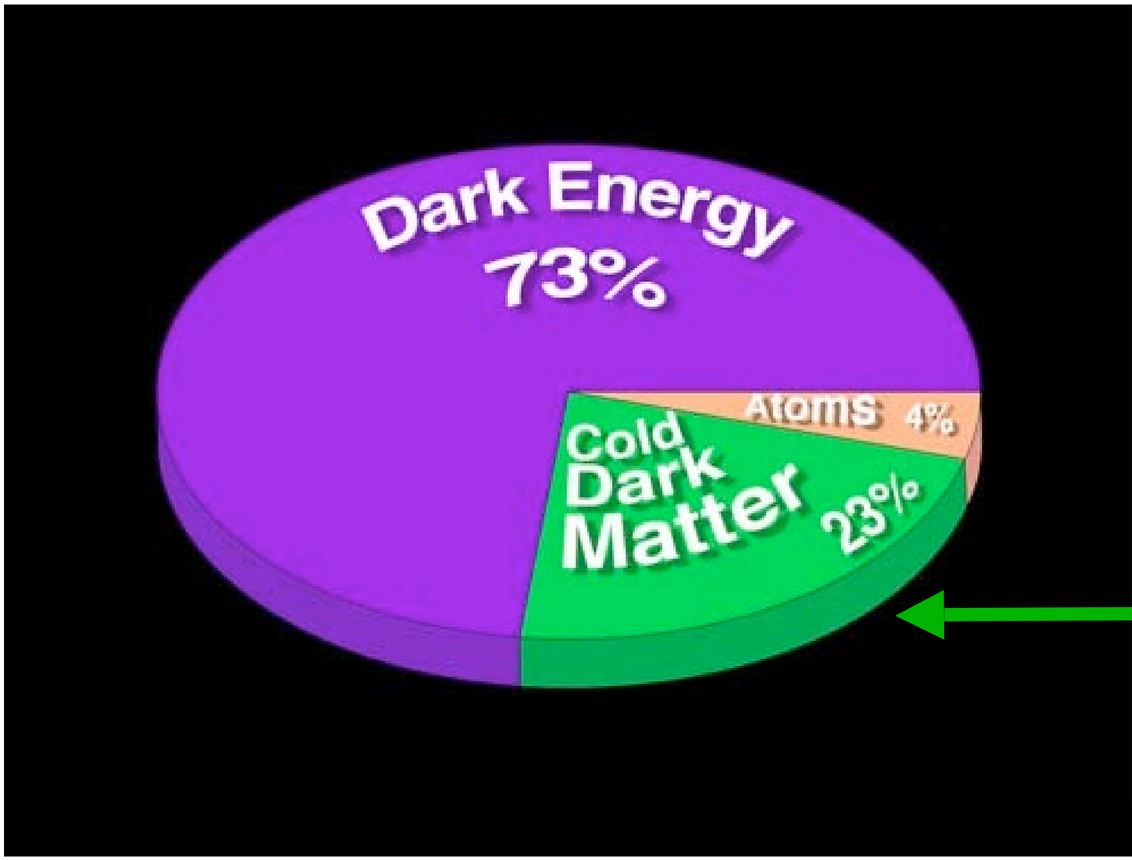
Standard Model of Astrophysics



<u>Many CDM candidates</u>
SUSY neutralinos
Axions
Q balls
Kaluza-Klein states
….

Most natural candidate:
Weakly-interacting
Massive Particle
(WIMP)

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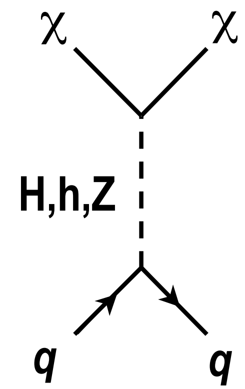
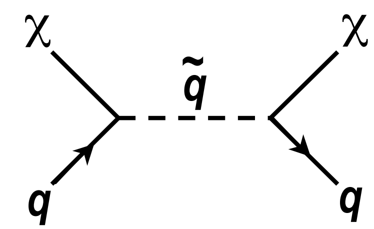
Direct Detection of WIMPs



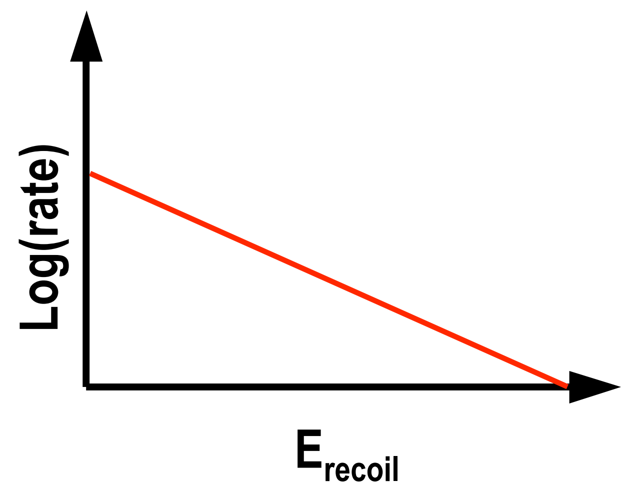


WIMPs elastically scatter off nuclei in targets, producing nuclear recoils, with $\sigma_{n\chi}$ related roughly by crossing to σ_A(~10^{-38} cm^2)

- Slow velocities ➔ large de Broglie λ ➔ coherent interaction with all nucleons
  - Spin-independent interaction $\propto A^2$
  - Spin-dependent needs target with net spin
- Loss of coherence minimizes advantage of largest-A targets

Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo

- Standard assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution
- V_0= 230 km/s, v_{esc}= 650 km/s,
- ρ = 0.3 GeV / cm^3



Energy spectrum of recoils is featureless exponential with $\langle E \rangle$ ~ 50 keV

Rate (based on $\sigma_{n\chi}$ and ρ) is smaller than 1 event per kg material per day

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Experimental Challenges for Direct Detection of WIMPs

- keV energy threshold
  - Sensitivity to low mass WIMPs
- Low radioactive contamination
  - Screening/purification of materials
  - Clean surfaces
    - Dust (U/Th/K)
    - Radon (daughter implantation)
- Background suppression
  - Deep sites (reduced cosmic ray flux)
  - Passive/active shielding
- Residual background rejection
  - Active nuclear recoil discrimination
  - Sensitivity improves:
    - Linearly with target mass and exposure time if no background
    - As $1/\sqrt{MT}$ by statistical subtraction of background
    - No further improvement if systematics of background subtraction dominate

- Signal Features
  - Location and type of interaction
    - Surface versus bulk
      - Backgrounds preferentially on surfaces, WIMPS interact anywhere
    - Electron versus nuclear recoil
      - Backgrounds cause electron recoils, WIMPS cause nuclear recoils
    - Multiple versus single scatter
      - Backgrounds multiple-scatter; WIMPS don't
  - Annual modulation
    - Surfing the WIMP "wind"
  - Diurnal modulation
    - Detect recoil direction
- Scale to large target mass
  - Maximize # of WIMP interactions
- Different target nuclei
  - Determine if possible signal from WIMPs or backgrounds

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A ‘typical’ experiment - CDMS

Dark Matter Search

Goal is direct detection of WIMP halo that holds our galaxy together

Cryogenic detectors

Cool very pure Ge and Si crystals to < 50 mK using dilution refrigerator

Active Background Rejection

Detect heat and charge

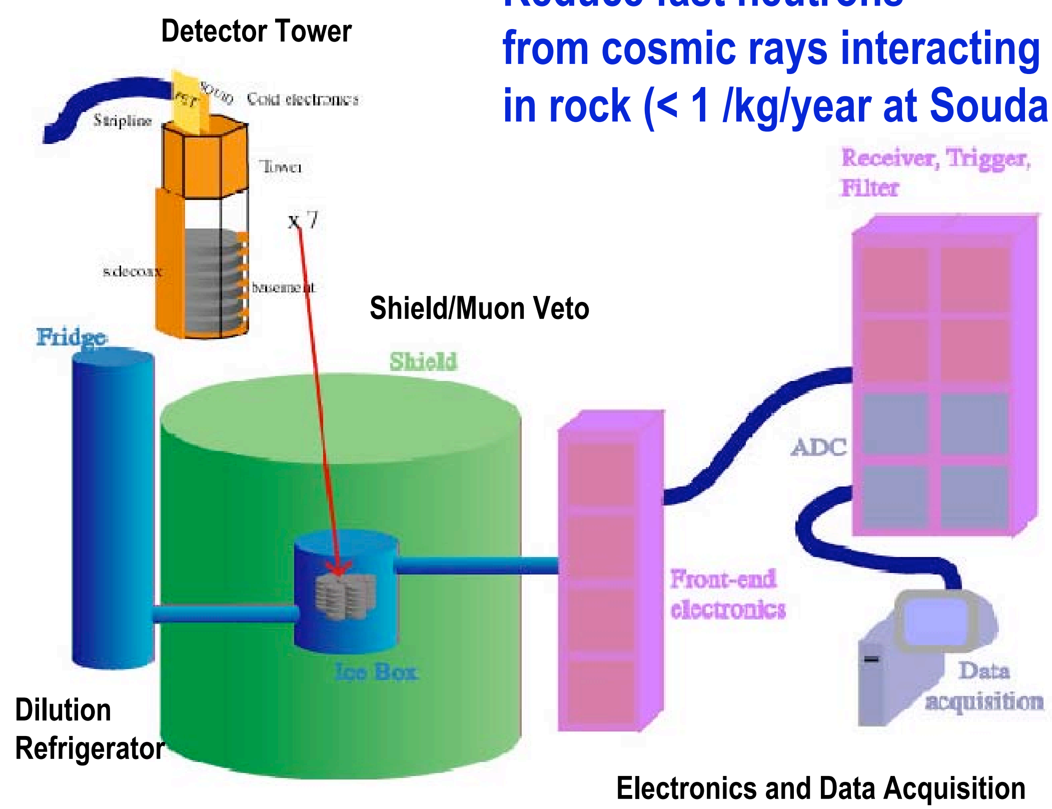
- WIMPS, neutrons => nuclear recoils
  - Charge/Heat ~ 1/3
- EM backgrounds => electron recoils
  - Charge/Heat = 1

Reject Neutrons

- Neutrons multiple scatter, WIMPS don’t
  - Look for single scatters
- WIMP cross sections x5 higher in Ge than in Si but neutron cross sections similar.
  - Look for Ge recoils, not Si

Deep Underground

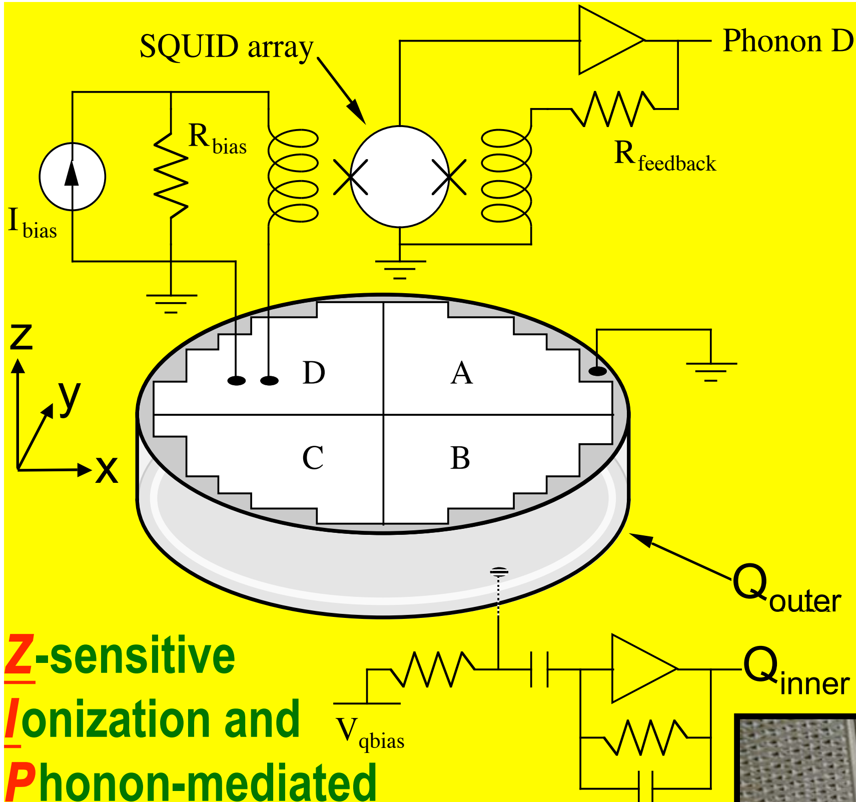
Reduce fast neutrons from cosmic rays interacting in rock (< 1 /kg/year at Soudan)



Shielding

Layered shielding (Pb, polyethylene, Cu) against radioactive backgrounds and active scintillator veto (>99.9% efficient against cosmic rays).

Really Cool Detectors: ZIPs



Z-sensitive
Ionization and
Phonon-mediated

250 g Ge or 100 g Si crystal

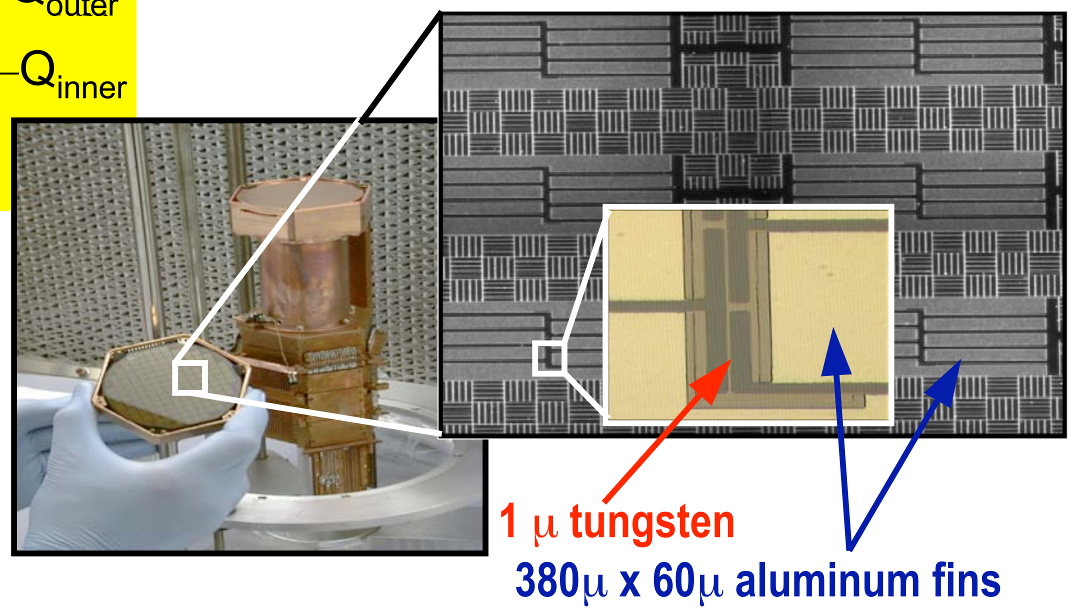
1 cm thick x 7.5 cm diameter

Photolithographic patterning

Collect athermal phonons:

- **XY position imaging**
- **Surface (Z) event veto based on pulse shape risetime**

Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge



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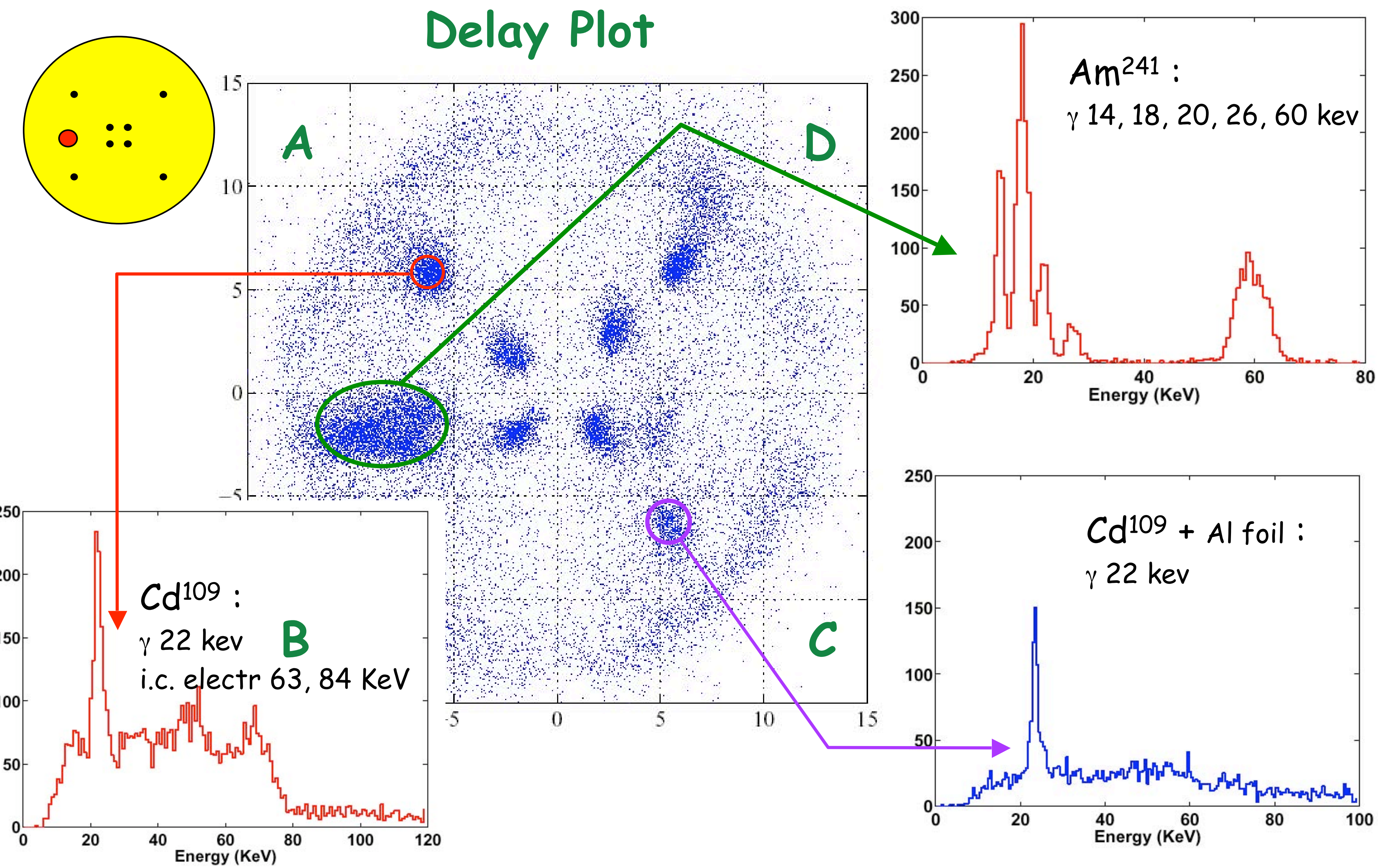
Demonstration of ZIP Position Sensitivity



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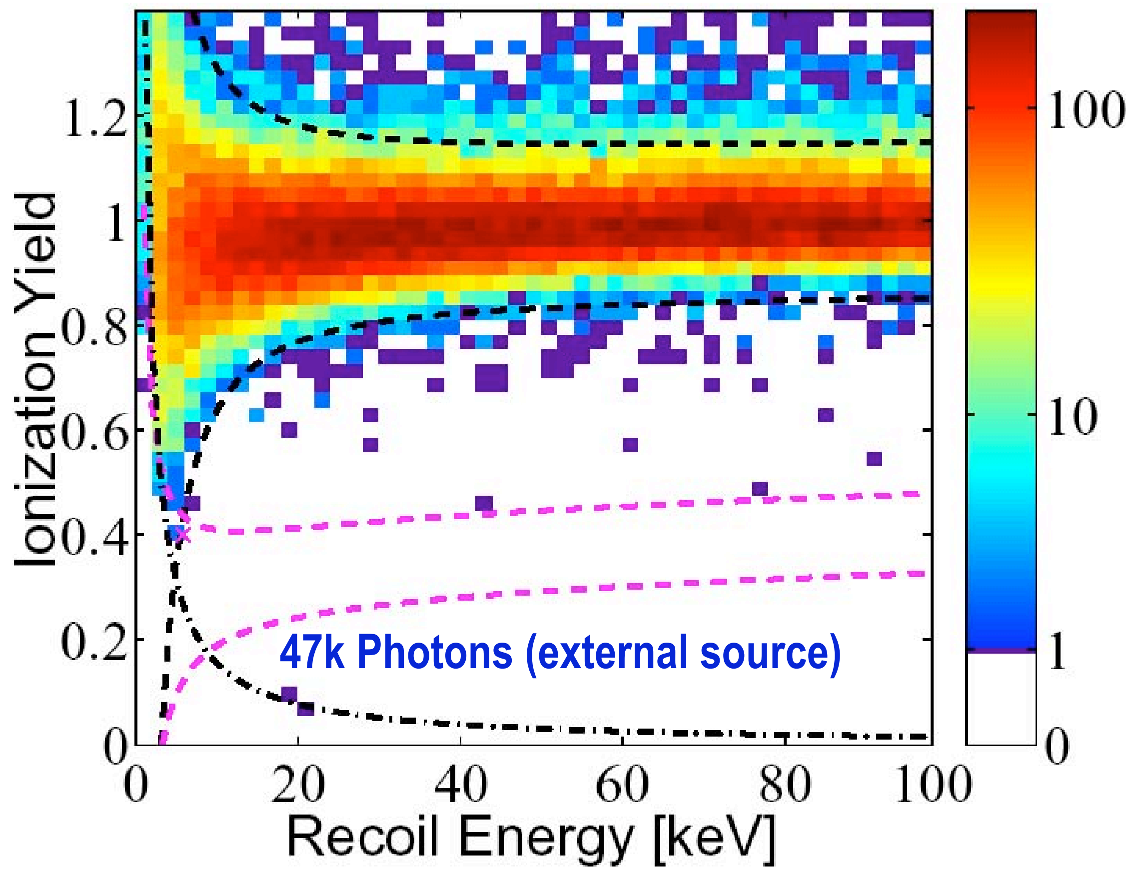
CDMS II Background Discrimination

Ionization Yield (ionization energy per unit recoil energy) depends strongly on type of recoil

Most background sources (photons, electrons, alphas) produce electron recoils



CDMS II Background Discrimination

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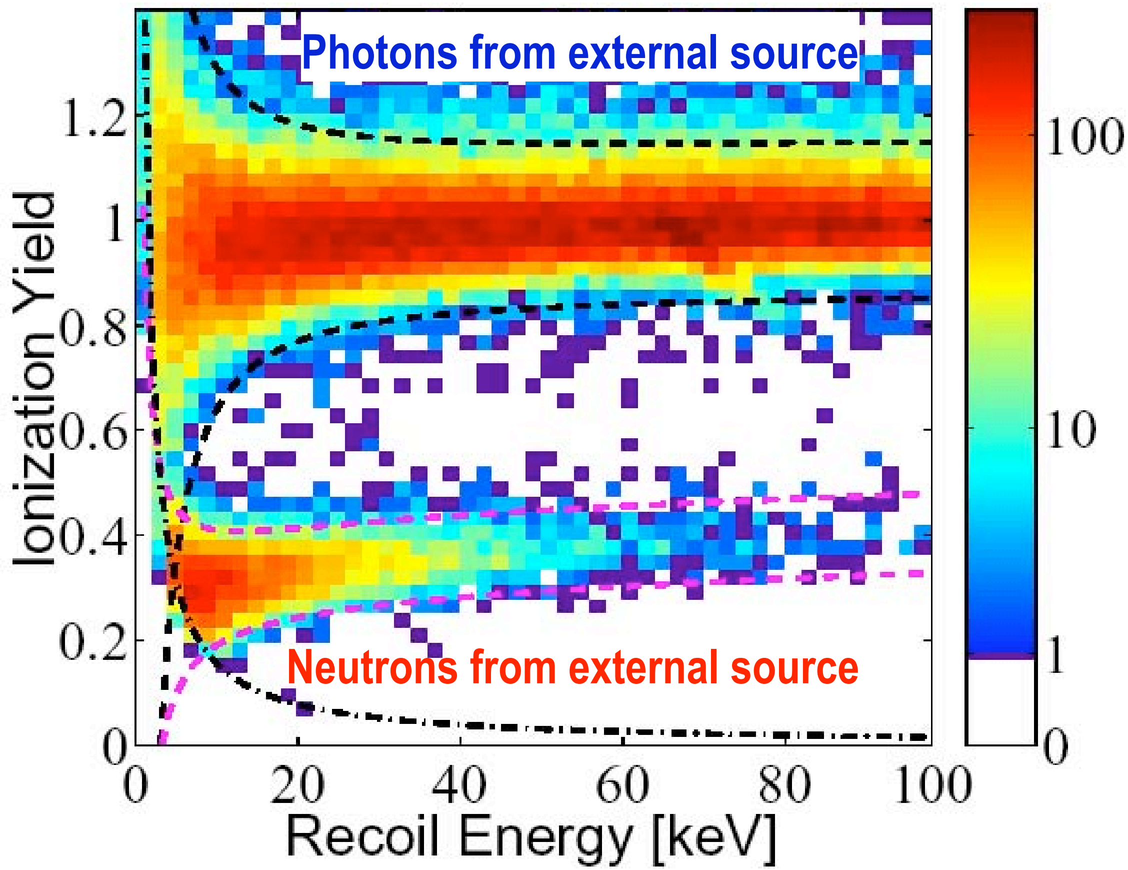
WIMPs (and neutrons) produce nuclear recoils



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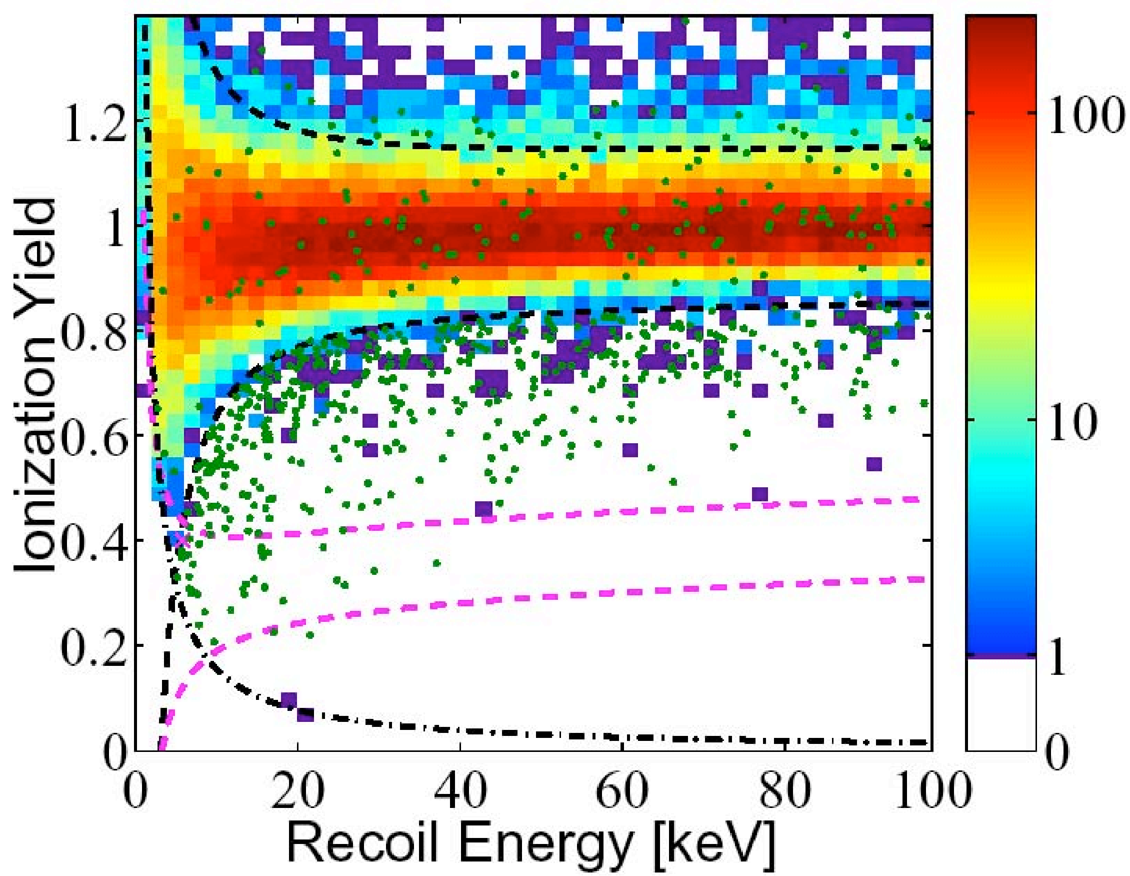


- Detectors provide near-perfect event-by-event discrimination against otherwise dominant bulk electron-recoil backgrounds
- Particles (electrons) that interact in surface "dead layer" of detector result in reduced ionization yield

The ‘Z’ in ZIPs: Electron Risetime Discrimination

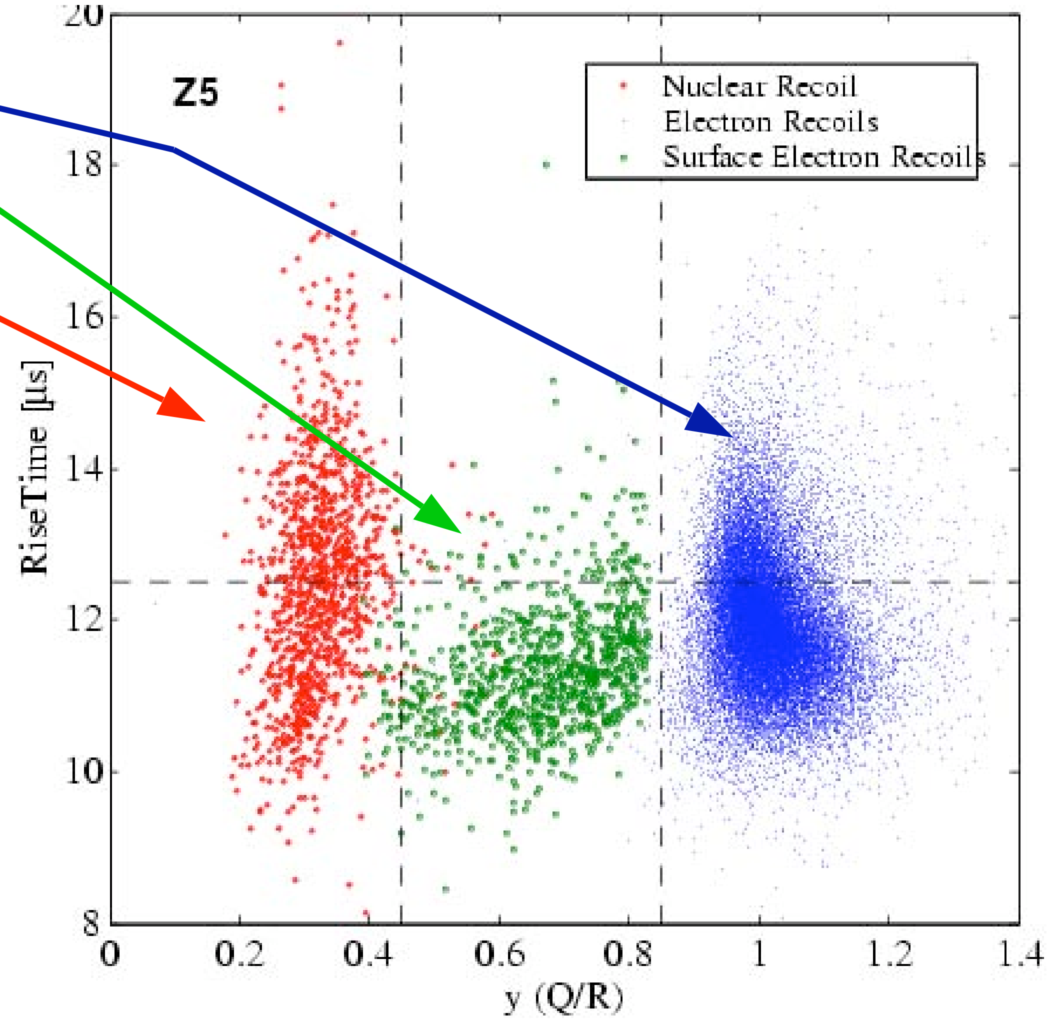
3 populations

- Electron recoils in bulk
- Surface events
- Nuclear recoils in bulk

Surface events produce faster phonons: 2nd discrimination parameter

- Pulse risetime and delay from charge pulse

Important second handle on electron backgrounds with ‘tail’ in charge yield



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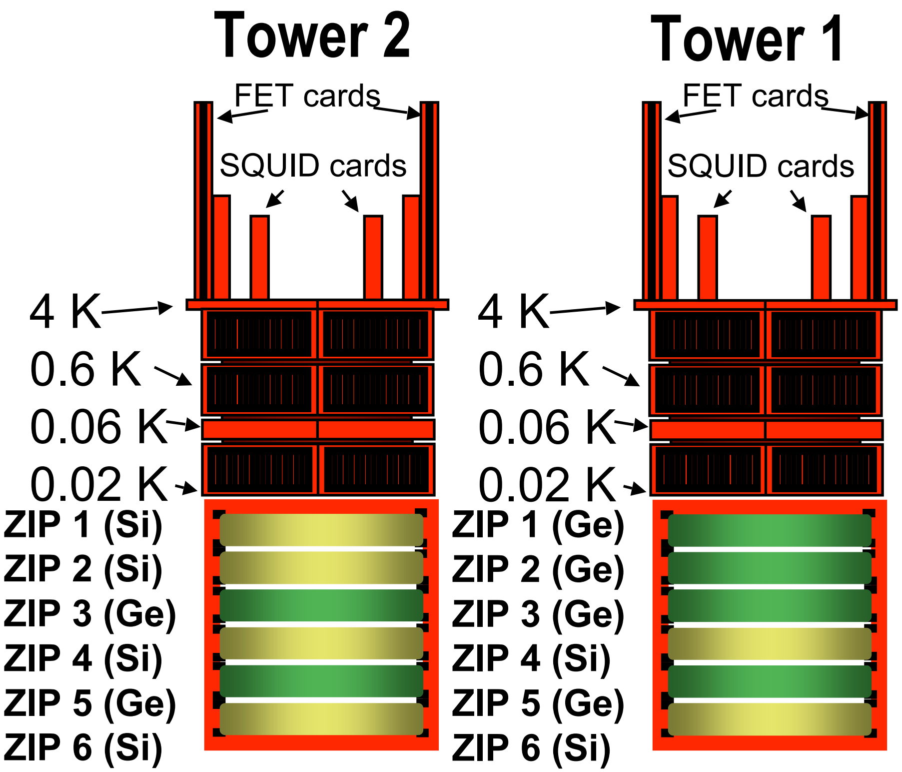
First Data from CDMS II at Soudan

October 2003- January 2004 run of "Tower 1"

- 4 Ge (0.85 kg) and 2 Si (0.17 kg) ZIPs
- 62 "raw" livedays, 53 livedays after cutting times of poor noise, etc.
- Expect all background sources combined to contribute < 1 event
- Set cuts while "blinded," opened box on March 20
- Detailed checks since then
- Preprint released on Monday, May 3

February 2004 - summer 2004 run of Towers 1 & 2

- 6 Ge (1.5 kg) and 6 Si (0.6 kg) ZIPs
- Similar backgrounds to Tower 1
- Simultaneous running of all 12 detectors since February



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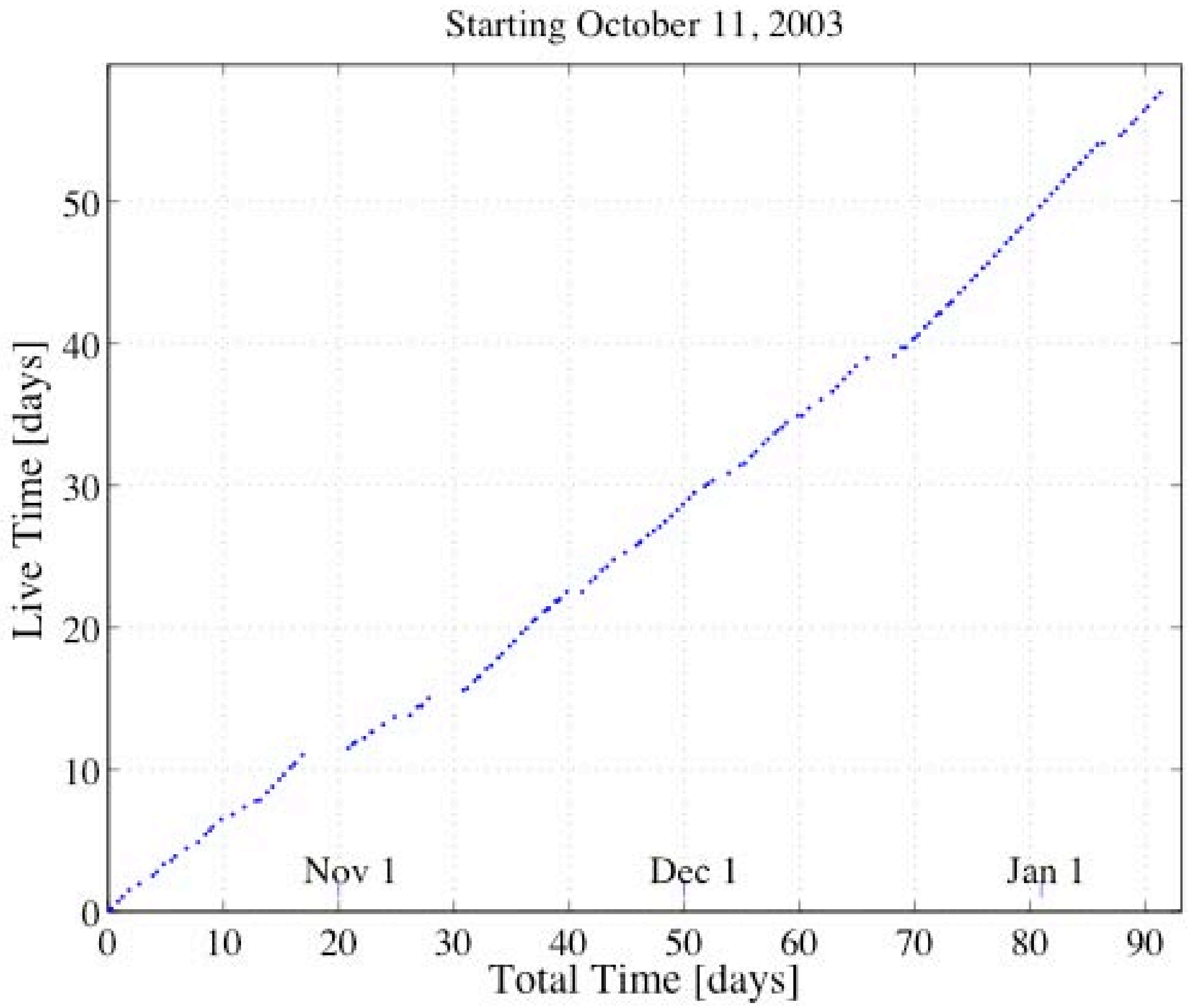
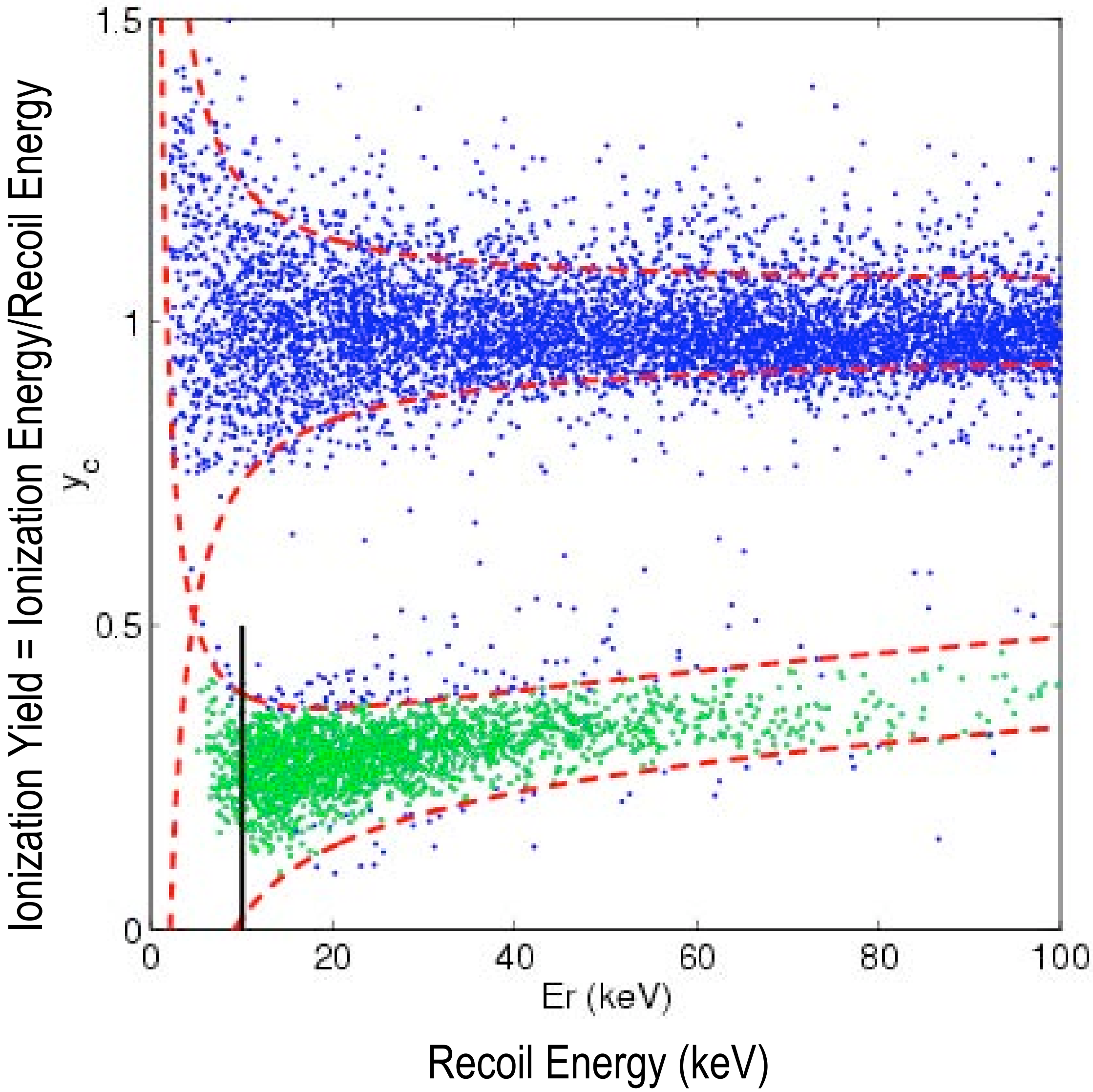
Excellent live time efficiency (for a first run)

- Collected 52.6 live days during 92 calendar days
- Efficiency nearly 85% for last six weeks
- Gaps were calibration runs with minimal cryo-lapses



^{252}Cf Neutron & Gamma calibration data

- Upper red dashed line are +/- 2 σ gamma band
- Lower red dashed line are +/- 2 σ nuclear recoil band
- Phonon non-uniformity corrected with high statistics gamma calibrations
- Bands and cuts determined with calibration data as was the analysis threshold energy



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Phonon timing + yield

Rejection of surface electrons (low energy betas)

- Use phonon risetime and charge-to-phonon delay

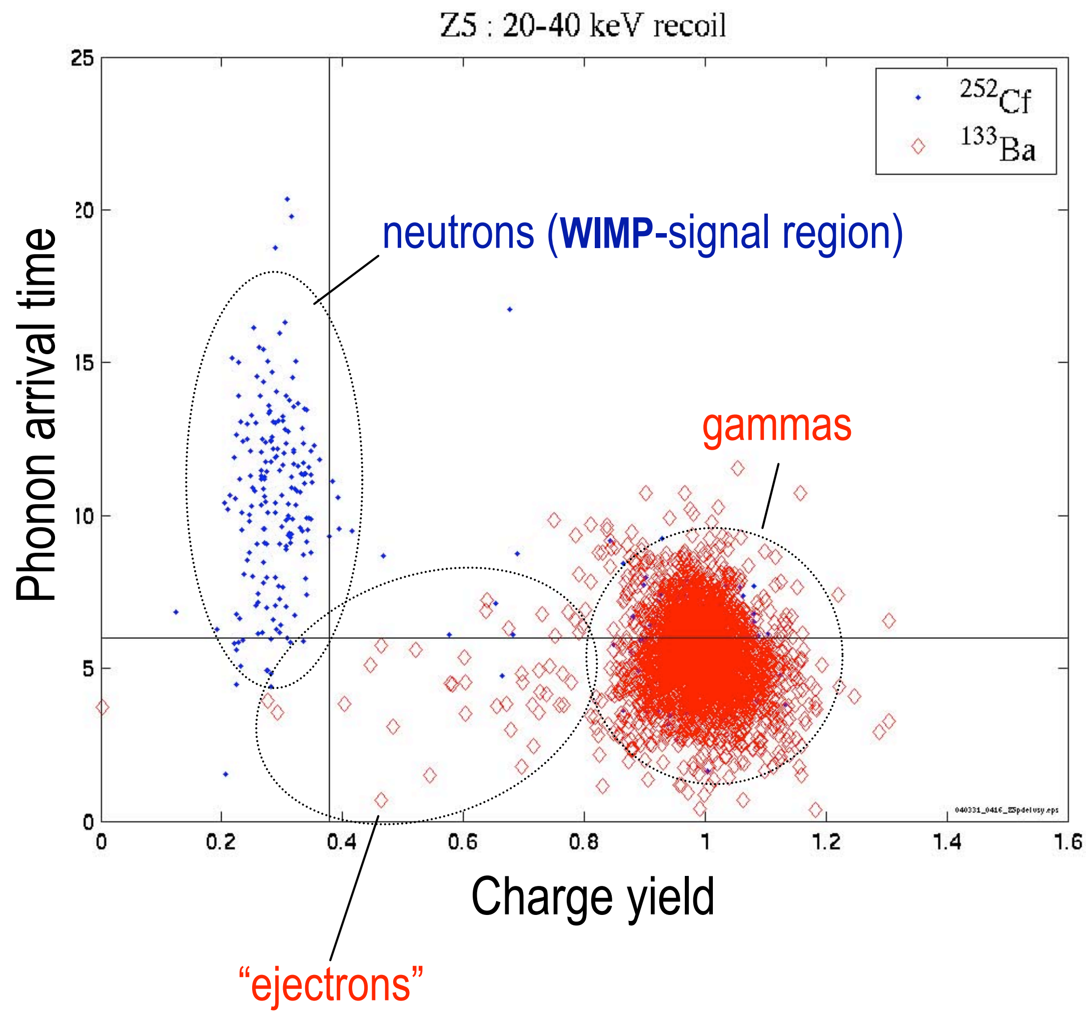
"Blind" Analysis

- Cuts and energy threshold based on *calibration data*
- WIMP-search data blinded until analysis 'fixed'
- Simplest possible cuts

NOT optimized

- We already can do better on both background rejection and nuclear recoil acceptance.

^{252}Cf neutron & ^{133}Ba gamma calibrations



WIMP search data with Ge detectors

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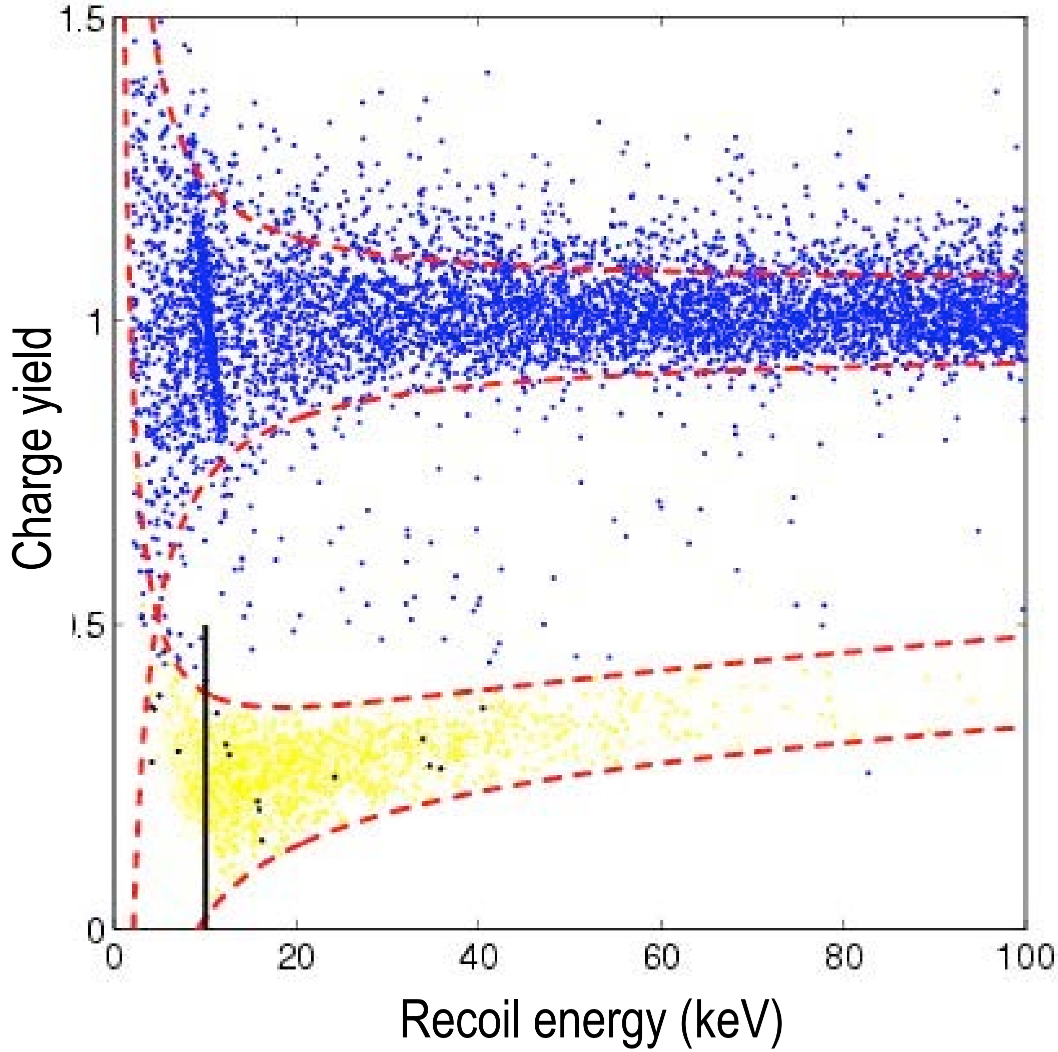
Exposure

- 92 days (October 11, 2003 to January 11, 2004)
- 52.6 live days
- 20 kg-d net (after cuts)
- 53% nuclear recoil acceptance

Data: Yield vs Energy

- Timing cut off
- Timing cut on
- Yellow points from neutron calibration



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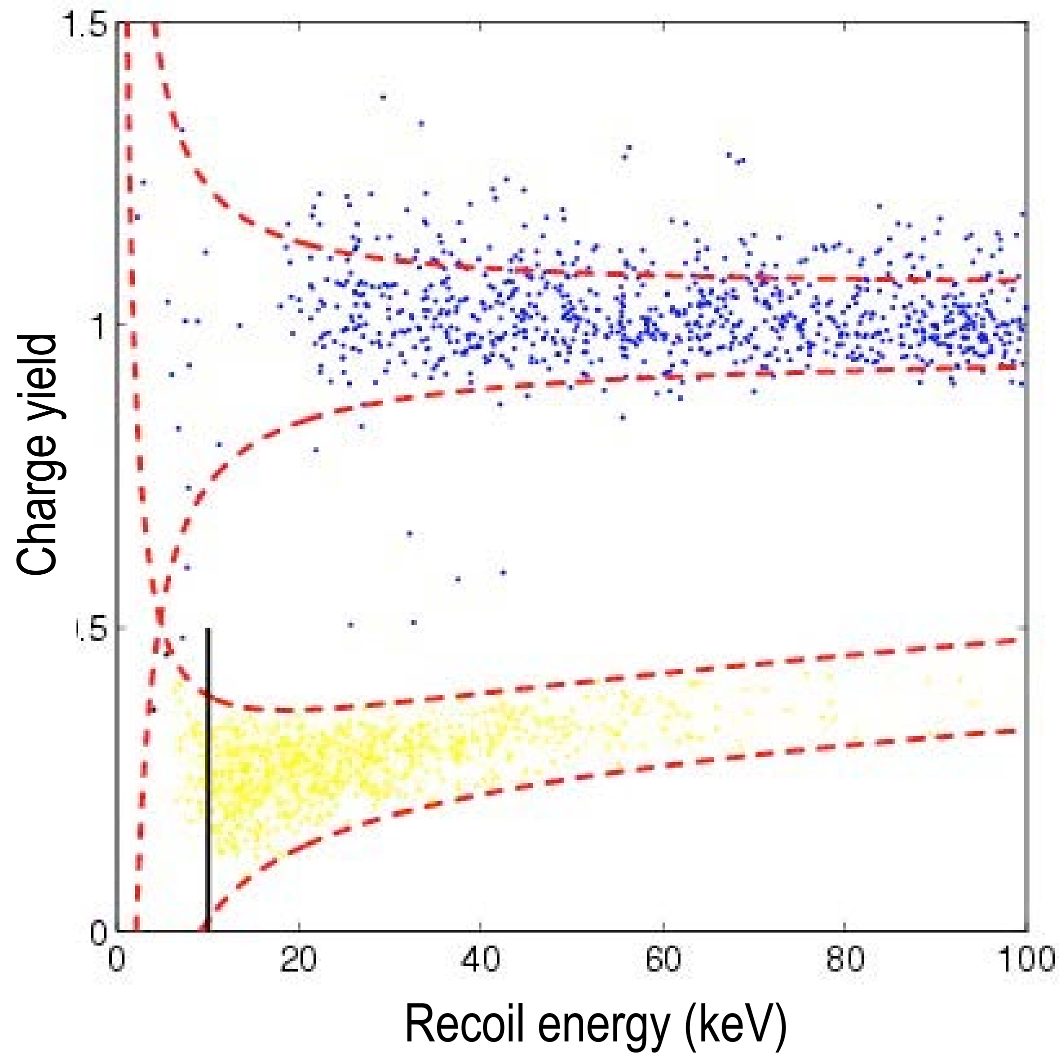

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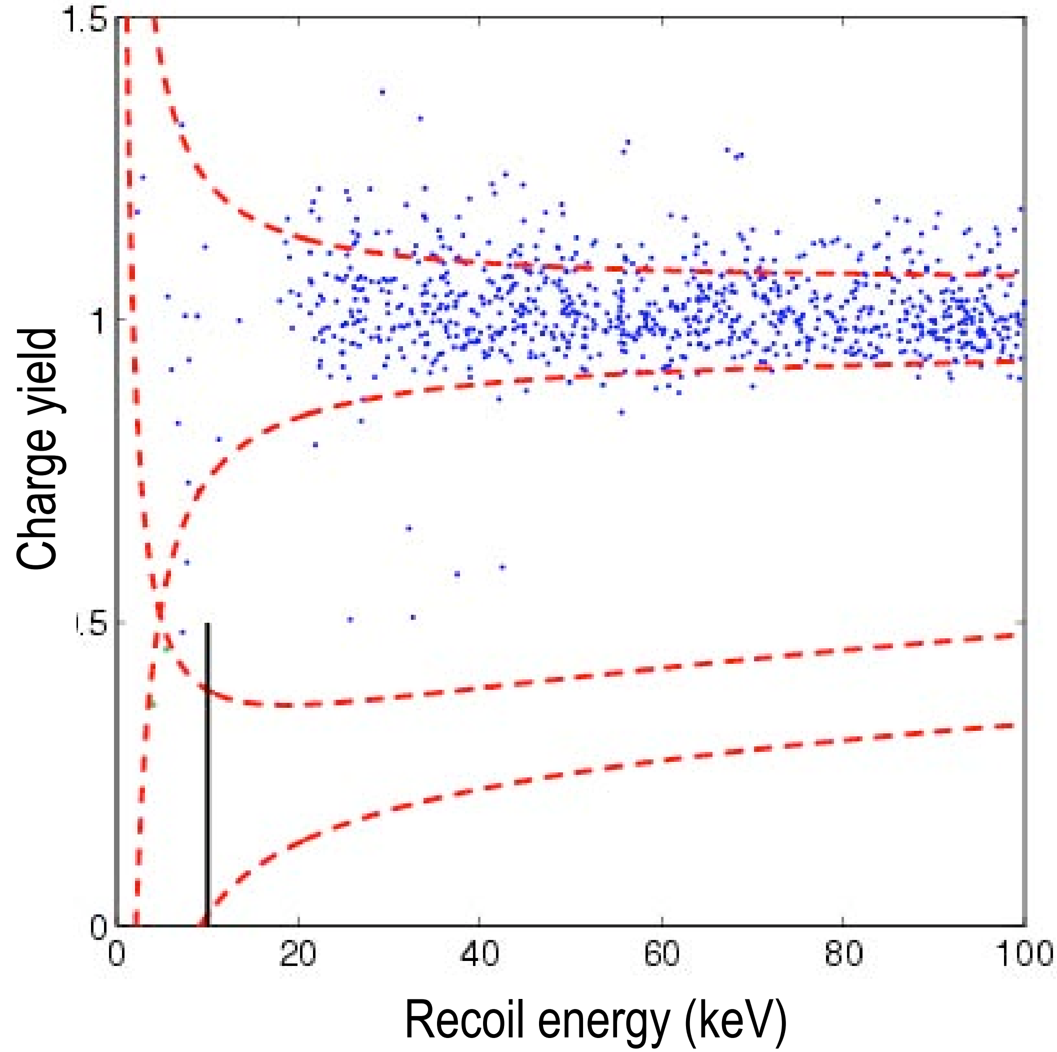

No nuclear-recoil candidates

WIMP search data with Ge detectors

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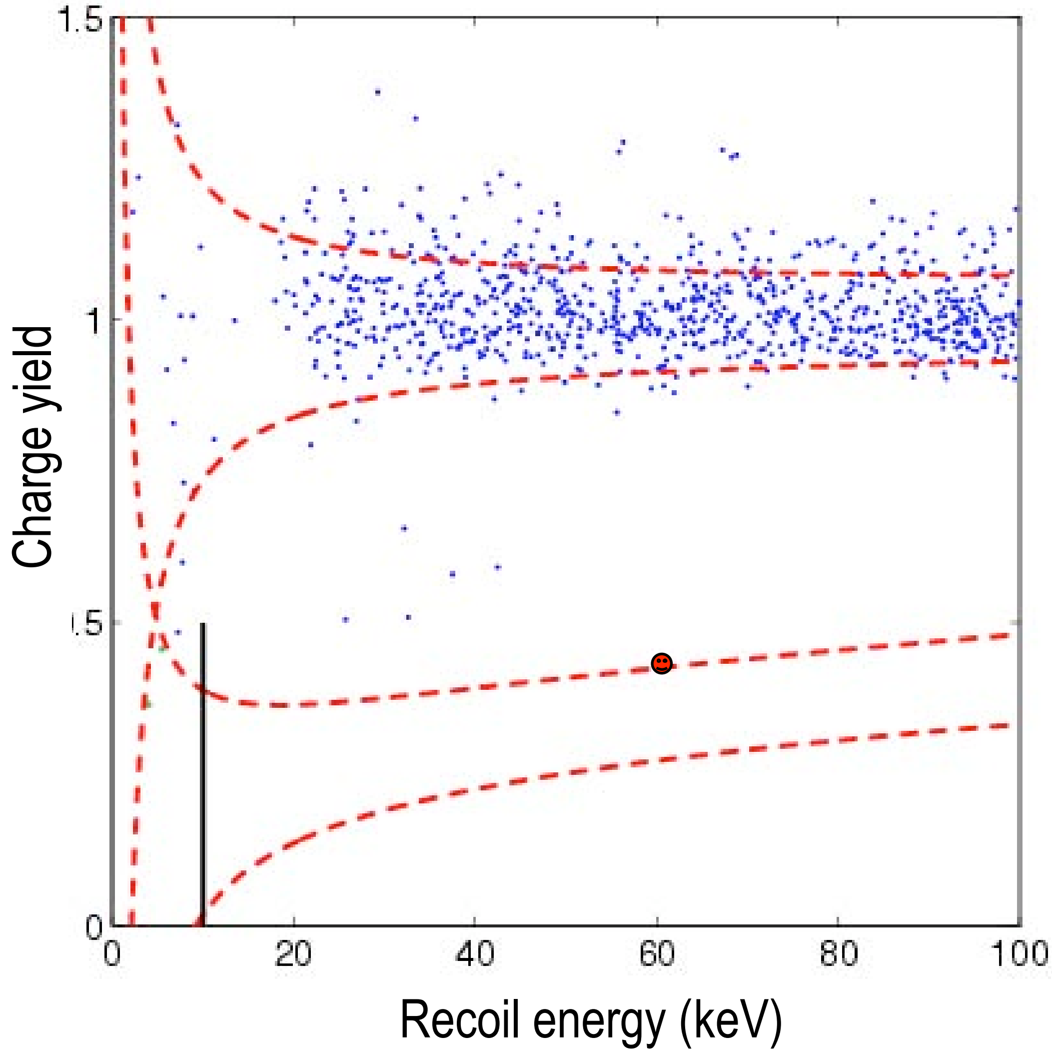

Well, maybe 1….

Expected beta background = 0.7 +/- 0.3 events

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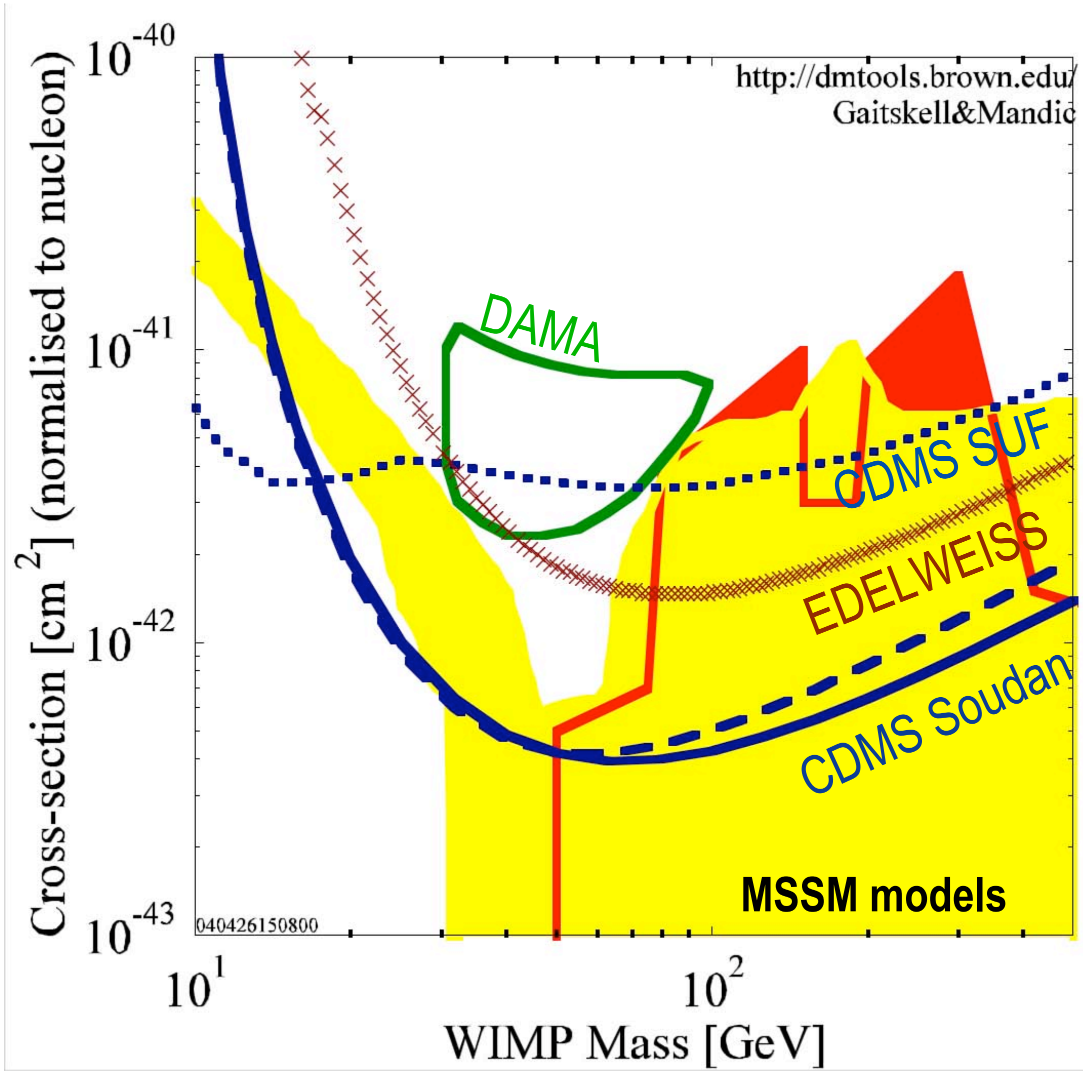
NEW CDMS limit from Soudan

- Exposure after cuts of 52.6 kg-d raw exposure with Ge ≈ 20 kg-days for 60 GeV/c^2 WIMP
- No nuclear-recoil candidates
- Expect ~1 mis-identified beta
  - Second non-blind analysis has 1 candidate (dashed limit curve show effect of this)
- Expect 0.1 unvetoed neutrons (1.0 muon coincident neutron)
- New limit ~4x (x10) better than EDELWEISS (CDMS SUF) at a WIMP mass of 60 GeV/c^2
- Really hard to accommodate DAMA annual modulation effect as a WIMP signal!
- Starting to seriously constrain MSSM models



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What's next for CDMS?

Improve our analysis

- Reduce analysis threshold to 5 keV (better low-mass WIMP sensitivity)
- Improved cuts to reject betas, improve nuclear recoil efficiency (but no longer blind)
- Expected exposure: 100 kg-d   Limit: 90% CL : 1.5×10^{-43} cm^2

Towers 1 and 2 are currently taking data -> July 04

- 50% more Ge, 100% more Si than in first run
- Use blind analysis for this independent sample, based on best version of Tower 1 analysis

Install 3 additional detector towers in September 04

- Total of 4.5 kg Ge, 1.2 kg Si
- New towers have improved handling, hopefully lower beta backgrounds

Run all 5 Towers January-December 31, 2005

- Exposure: 1,200 kg-d   90% CL upper limit: 2×10^{-44} cm^2
- If we're lucky, a WIMP signal begins to appear!

Reduce beta and neutron backgrounds even further

- Detector optimization, Beta screening of materials, additional scintillator veto

Construct two more towers and run through 2008 (CDMS III)

- Exposure: 4,800 kg-d   90% CL upper limit: $< 7 \times 10^{-45}$ cm^2
- Would allow us to explore any signal which starts to appear in CDMS II

Comparison with Competition

DAMA - NaI

- Very limited discrimination; must rely on 2% annual modulation effect
- Systematic effects near energy threshold hard to control
- Only WIMP signal reported thus far (6 years of annual modulation data)

EDELWEISS - Ge thermal and ionization

- Slower thermal detector technology (no additional rejection from timing)
- Very deep site, but no Si detectors to measure neutrons when they appear
- Begin running in 2005 with substantial target mass.

CRESST - Ca_2WO_4 thermal and scintillation

- Very low threshold but no light for W & O nuclear recoils
- Have problems with phonon-only signals from alphas
- Need additional shielding/veto; begin running again in 2005?

ZEPLIN, XENON and XMASS - Xe ionization and scintillation

- Must demonstrate sufficiently low energy threshold (time scale is 2006)
- Light for nuclear recoils not yet demonstrated
- Clearest path towards large target mass in the long-term

DRIFT - CS_2 low pressure gas TPC

- Only technology capable of determining event direction
- Difficult to instrument 5-10 kg of target in near future

Heavy Liquid Bubble Chamber (Collar, Sonnenschein - Univ. Chicago)

- Very impressive discrimination against backgrounds in small prototype
- Larger prototype may be tested at Soudan in 2005

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Summary and Projections

WIMPs

- Looking for 23% of the universe!
- New particle physics (SUSY neutralino)
  - Sensitive to 10-10000 GeV masses
  - Challenging MSSM models

Broad range of experimental approaches/efforts

- CDMS II at Soudan leads the chase
- Significant competition by next year

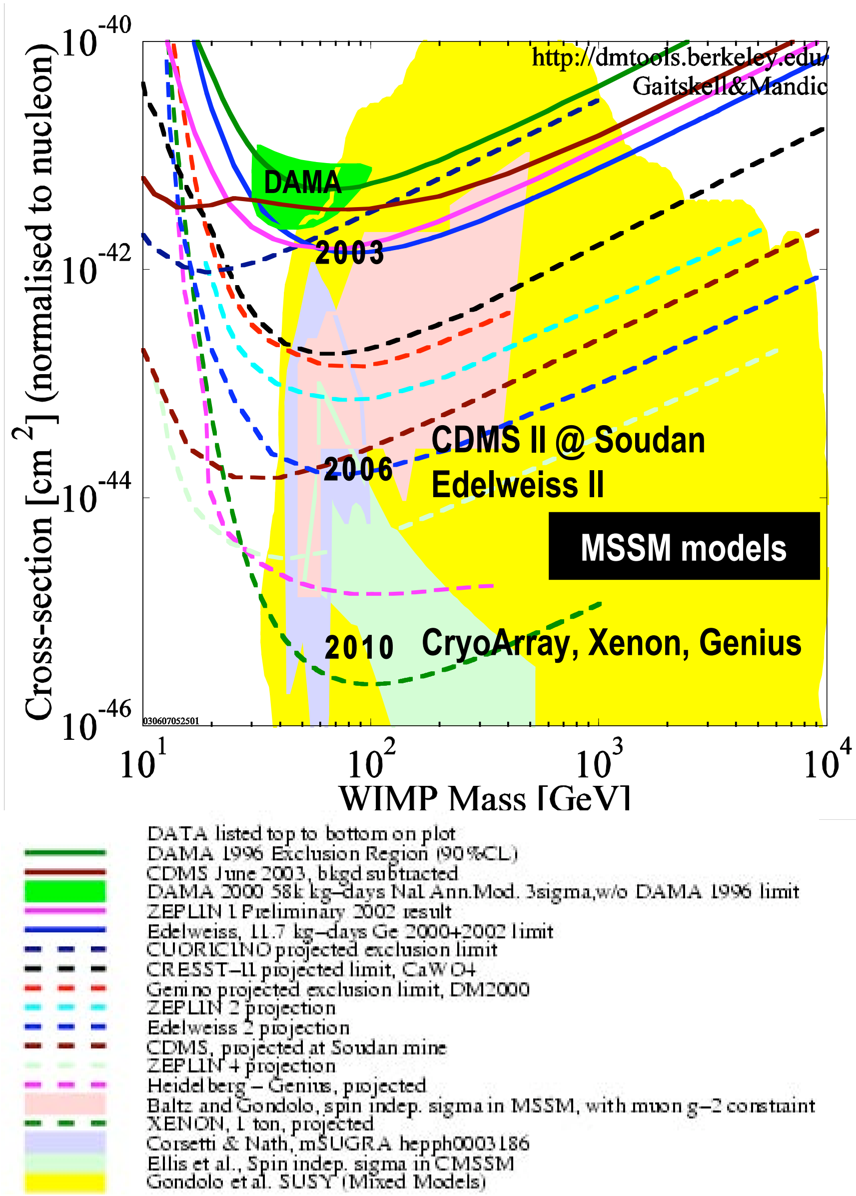
Expansion to ton-scale detector mass

- Several approaches possible, none demonstrated
- Results from next few years will decide

Growing scale of experiments

- Room for increased HEP participation
- DUSEL - Deep Underground Science and Engineering Laboratory needed by 2010
- Shorter-term requires low background screening facility - proposal at Soudan

90% CL upper limits assuming standard halo, A^2 scaling



CDMS Collaboration